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MATERIALS RESEARCH HIGHLIGHT

Metamaterials for threat reduction applications: imaging, signal processing, and cloaking

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The development of artificially structured materials, termed metamaterials (MM), has dramatically expanded our view of electromagnetic material interactions. These sub-wavelength composites can be designed to exhibit electromagnetic responses allowing for the realization of phenomena not available with natural materials.

This is especially important for the technologically relevant terahertz (1 THz = 10^{12} Hz) frequency regime since many electronic materials do not respond to THz radiation and thus, the tools necessary to construct devices operating within this range—sources, switches, modulators, detectors —largely do not exist.

Considerable effort is underway to fill this "THz gap" in view of potential threat reduction applications such as short-range secure communication and spectroscopic imaging. The design flexibility associated with metamaterials provides a promising approach—from a device perspective—towards filling this gap.

With Laboratory-Directed Research and Development Directed Research (LDRD-DR) support, scientists in the Center for Integrated Nanotechnologies, in collaboration with colleagues from International, Space & Response (ISR) and Theoretical Divisions, are exploring metamaterials-based devices operating at THz frequencies for threat reduction applications. This includes metamaterial devices for modulating and detecting terahertz radiation and utilizing advanced electromagnetic simulation to design and fabricate non-planar metamaterials to reduce the electromagnetic scattering cross-section of objects.

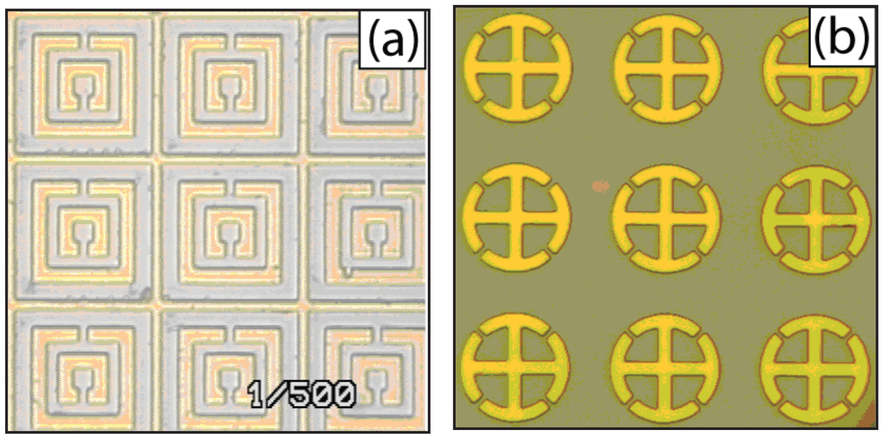

Figure 1: Magnetic and electric metamaterials. Planar array of (a) split ring resonator "particles" and (b) purely electric resonators. These devices (unit cell 50μm X 50μm) exhibit a magnetically (a) and electrically (b) resonant response at terahertz frequencies.

Metamaterials are sub-wavelength composites where the electromagnetic response originates from oscillating electrons in highly conducting metals, such as gold or copper, allowing for a design specific resonant response of the electrical or magnetic response. Split ring resonators (SRR) are the most common metamaterial "particle."

Figure 1 shows examples of planar arrays of SRRs fabricated on gallium arsenide substrates. In simple terms, a SRR behaves as a resonant LC circuit—the solenoidal structure provides the inductance L and the capacitance C is obtained from the split gap. Crucially, the capacitance can be modified (or shunted) through external stimulus resulting in a change of the resonant response of the metamaterials. Importantly, the symmetry of the particles dictates, in part, the electromagnetic response. The particles in Fig 1(a) can support a magnetic response while those in Fig 2(a) have a purely electric response.

Optically induced dynamical control of metamaterials was recently demonstrated by modifying the SRR capacitance[1]. A planar array of SRRs was patterned on a semi-insulating gallium arsenide (SI-GaAs) substrate and photodoping was used to control and modify the substrate properties. Representative data from this work is displayed in Figure 2. In this particular experiment, the conductivity arising from mobile photocarriers shunts the low-frequency resonance at ω_0 = 0.5 THz associated with circulating currents.

This work has revealed the potential of SRR/semiconductor hybrid structures to develop THz switches.

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Metamaterials provide a new scale-invariant design paradigm to create functional materials that potentially revolutionize our ability to manipulate, control, and detect electromagnetic radiation.

Richard Averitt received his PhD in applied physics from Rice University in 1998. The Los Alamos technical staff member is the thrust leader for complex functional nanomaterials for the Center for Integrated Nano-technologies. His primary research interest is time-resolved and time-integrated optical spectroscopy of condensed matter including correlated electron materials and transition metal oxides, plasmonic nanostructures, metamaterials such as split ring resonators, and semiconductor heterostructures.

Antoinette Taylor is the Center for Integrated Nanotechnologies associate director. She received her PhD in physics from Stanford University and is a fellow of the American Physical Society and Optical Society of America. Taylor's primary research interests are in the area of nano-photonics and complex functional nanomaterials, with an emphasis on optical interactions with nanomaterials and the development of novel optics-based techniques to study nanoscale phenomena.

Willie Padilla earned his PhD in physics at the University of California, San Diego. He was a Director's funded postdoctoral researcher in MPA-CINT and is currently an assistant professor of physics at Boston College.

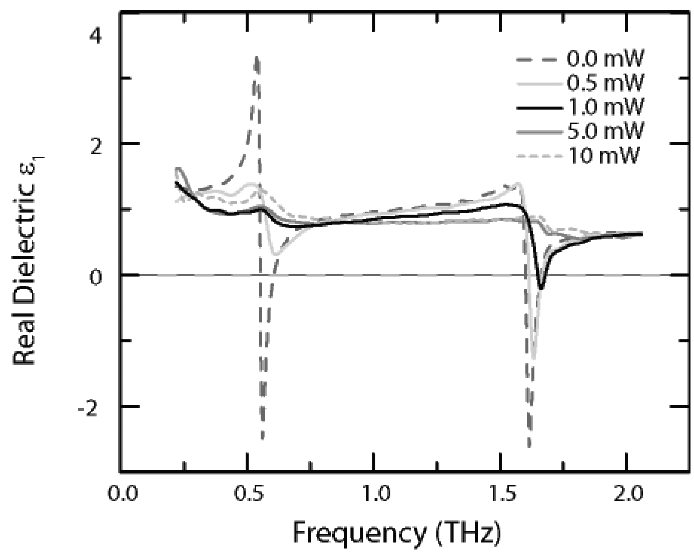

Figure 2: Real part of the metamaterial permittivity (of the planar array shown in Fig. 1(a)) at terahertz frequencies at various optical powers. Gentle photoexcitation (1 mW g10^{16} carriers per cubic centimeter), shunts the resonant metamaterial response.

Since the SRR array was fabricated on SI-GaAs, the switching time is limited to the intrinsic recombination time (>1 ns). Future work in this area will focus on creating faster devices using substrate materials with shorter recombination times and on voltage-controlled active metamaterial devices.

In summary, metamaterials provide a new scale-invariant design paradigm to create functional materials that potentially revolutionize our ability to manipulate, control, and detect electromagnetic radiation.

Research and development in metamaterials represents a strategic growth opportunity for the Laboratory in the threat reduction arena, providing an avenue for applying the Materials Physics and Applications Division's forefront materials fabrication, design, and characterization capabilities in partnership with ISR's detection and sensor expertise.

References

[1]W. J. Padilla, A. J. Taylor, C. Highstrete, M. Lee, and R. D. Averitt, "Dynamical electric and magnetic metamaterial response at terahertz frequencies," *Phys. Rev. Lett.*, **96**, 107401 (2006).